Thermal wave interference as the origin of the overshooting phenomenon in dual-phase-lagging heat conduction

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ABSTRACT

In the present work, the overshooting phenomenon is investigated based on the one-dimensional dual-phase-lagging heat conduction model. The thermal wave interference is found to trigger the overshooting of temperature field. A condition for the occurrence of overshooting phenomenon is established for the one-dimensional dual-phase-lagging heat conduction in a finite medium. According to this condition, the overshooting phenomenon may occur in heat conduction across gold films with the thickness ranging from 4.8555 nm to 19.581 μm.

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1. Introduction

As the fundamental law in heat conduction, the Fourier law reads,

\[ q(r, t) = -k \nabla T(r, t) \]  (1)

where \( \nabla T(r, t) \) is the temperature gradient which is a vector function of the position vector \( r \) and the time variable \( t \), \( q(r, t) \) is the heat flux, \( k \) is the thermal conductivity of the material which is a positive scalar quantity. The Fourier law has wide and successful applications in the conventional thermal systems which have large spatial dimension with the focus of its long time behavior. However, some problems appear when the Fourier law is employed for those involving the ultrafast heating and/or micro/nano-scale heat conduction. Firstly, the Fourier law leads to the infinite speed of heat propagation, implying that a thermal disturbance applied at a certain location in a medium can be sensed immediately anywhere else in the medium [1]. Secondly, because the heat flux and the temperature gradient are simultaneous, one can not tell which is the cause or effect of heat flow. This becomes critical for the transient behavior at extremely short time, for example on the order of picoseconds to femtoseconds [2]. An example is the ultrafast laser heating in thermal processing of materials. Thirdly, experimental observations of the propagation of second sound, ballistic phonon propagation and phonon hydrodynamics in solids at low temperatures depart significantly from the usual parabolic description of heat conduction [1]. Fourthly, due to the rapid development of modern microfabrication technology, more and more tiny devices with micro- and nano-scale dimension emerge in various micromechanical and microelectronic systems. It is well known that when the characteristic time is comparable or less than the mean free time of heat carrier, the conventional Fourier law leads to the unaccepted result [3–5]. Recently, the validity of the Fourier law has also been examined for heat transport processes in the low-dimensional lattices [6–11].

Much effort has been devoted to the improvement of classical Fourier law. Cattaneo [12] and Vernotte [13] proposed the CV model.

\[ \tau \frac{\partial q}{\partial t} + q = -k \nabla T, \]  (2)

where \( \tau \) is the relaxation time. This model leads to a hyperbolic heat conduction equation which removes the issue of the infinite heat propagation speed. The natural extension of CV model is

\[ q(r, t + \tau) = -k \nabla T(r, t), \]  (3)

which is called the single-phase-lagging heat conduction model. A further improvement of model (3) leads to the following dual-phase-lagging (DPL) model [1].